

Observational Asteroseismology of Hot Subdwarf Stars

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Hot subdwarf stars are particularly challenging for asteroseismology due to their rapid pulsation periods, intrinsic faintness and relative rarity both in the field and in clusters. These features have ensured that the preferred method of observation up to now has been white-light photometry, and all asteroseismological solutions to date have been made by model fitting of the frequency spectrum. Several attempts have been made to perform asteroseismology using time-resolved spectroscopy on the brightest of these stars, but with modest results. A few attempts at simultaneous multi-color photometry have also been made to identify modes with the amplitude ratio method. We will review the most recent observational results and progress in improving the observational methods for ground-based asteroseismology of these compact pulsators.

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1 Introduction

Hot subdwarf stars are mostly Extreme Horizontal Branch (EHB) stars, *i.e.* core helium burning stars with an envelope too thin to sustain hydrogen-shell burning. Not all sdB stars are EHB stars, since evolutionary tracks of post-RGB stars that fail to ignite helium also cross the subdwarf region on their way to the helium-core white dwarf (WD) stage. While the EHB term implies core He burning, the sdB/sdO terms are used to describe the spectroscopic appearance, and do not presume a particular evolutionary stage.

The canonical picture of the EHB stars was established by Heber (1986), in which the EHB stars are He core burning stars with masses close to the core He flash mass of $\sim 0.47 M_{\odot}$, and hydrogen envelopes too thin to sustain hydrogen burning (less than $\sim 1\%$ by mass). It is understood that they are post-RGB stars that have ignited He in a core flash just before or after the envelope was removed by any of several possible mechanisms. The lifetime of EHB stars from the zero-age EHB (ZAEHB) to the terminal age EHB (TAEHB), when core He runs out, takes between 100 and 150 Myrs, and the post-EHB evolution will take them through the sdO domain directly to the WD cooling curve without ever passing through a second giant stage. The time they spend shell He burning before leaving the sdO domain can be up to 20 Myrs (Dorman et al. 1993).

Although the future evolution of EHB stars after core He exhaustion has always been presumed quite simple, the paths that lead to the EHB are still somewhat mysterious. New hope that the evolutionary paths leading to the formation of EHB stars can be resolved has been kindled by the discovery that many of them pulsate, which has opened up the possibility of probing their interiors using asteroseismological methods. For an introduction to the interior structure of the EHB stars, and the pulsation driving mechanism

we defer the reader to the accompanying review paper by Kawaler (this issue). Here we will focus on the observed properties of EHB stars, and on the particular challenges for observational asteroseismology.

Hot subdwarf stars are often found as blue stars in surveys covering the galactic caps. The PG survey (Green et al. 1986) covered more than ten thousand square degrees at high galactic latitudes, and found 1874 UV-excess objects, of which more than 1000 were identified as hot subdwarfs, so these stars dominate the population of faint blue stars down to the PG survey limit ($B = 16.5$). Together with the large sample of subdwarfs detected in the HS survey and analysed by Edelmann et al. (2003), these have provided a rich source of hot subdwarfs for observers to follow up, and discoveries of new variables from these surveys are still made almost every year (see Østensen et al. 2010a, and references therein). The recent SDSS (Stoughton et al. 2002) also contains spectra of more than 1000 hot subdwarfs, but is dominated by the increasing fraction of faint galactic WD stars, which takes over as the dominant population around about $B = 18$ mag, at a distance which hot subdwarfs belong to the dilute halo population. The Subdwarf Database (Østensen 2006) lists ~ 2500 hot subdwarfs, with extensive references to the available literature.

Several surveys have attempted to tackle the question of the binary frequency of EHB stars, but the matter is complicated by the many different types of systems in which these stars are found. Hot subdwarfs with FGK companions are easily detected from their double-lined spectra or from IR excess. But such stars with WD or M-dwarf companions show no such features. When the orbital periods are sufficiently short, these systems can easily be revealed from their radial velocity (RV) variations. Using the RV method, Maxted et al. (2001) targeted 36 sdB stars and found 21 binaries, all with periods less than 30 days. This gave a frac-

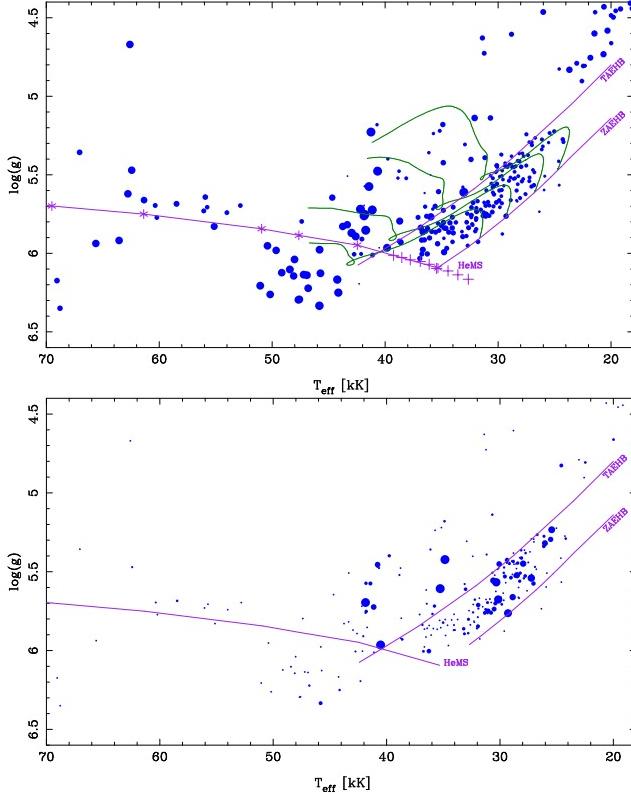


Fig. 1 The EHB in the T_{eff} – $\log g$ plane as observed by the Bok-Green survey (Green et al. 2008). The symbols mark observed stars with the size indicating the He abundance. The theoretical zero age HeMS is shown for a wide range of masses. Models from Paczyński (1971) with masses of 0.5, 0.7, 0.85, 1, 1.5 and $2 M_{\odot}$ are marked with * symbols (starting from low T_{eff}). More recent models from Kawaler & Hostler (2005) are shown for $M_* = 0.41, 0.43, \dots, 0.57 M_{\odot}$ and marked with + symbols. The ZAEHB and TAEHB for $0.47 M_{\odot}$ core models are also drawn. For the latter, four evolutionary tracks with different envelope thicknesses $\log M_e/M_* = -3.5, -3, -2.5, -2$ are drawn (starting from high $\log g$). Lower panel: As above, but with the symbol size indicating the dispersion in RV. The EHB stars with the highest velocity variations appear to be concentrated at lower gravities on the EHB. sdB+FGK stars are not included here, due to difficulties in reliably disentangling composite spectra. Figures from Østensen (2009).

tion of short period binaries of $60 \pm 8\%$. Other surveys have found smaller fractions, but they have not constrained the sample to focus strictly on the EHB. From high-resolution VLT spectra of 76 sdB stars Lisker et al. (2005) found that 24 showed the signature of an FGK companion, none of which showed any detectable RV variability. Napiwotzki et al. (2004) reported that of 46 sdB stars in the same sample, 18 (39%) were RV variable. Clearly, the binary fraction in EHB stars is substantially higher than for normal stars, but the exact number is hard to pin down since sample selection and survey sensitivity effects easily skew the numbers.

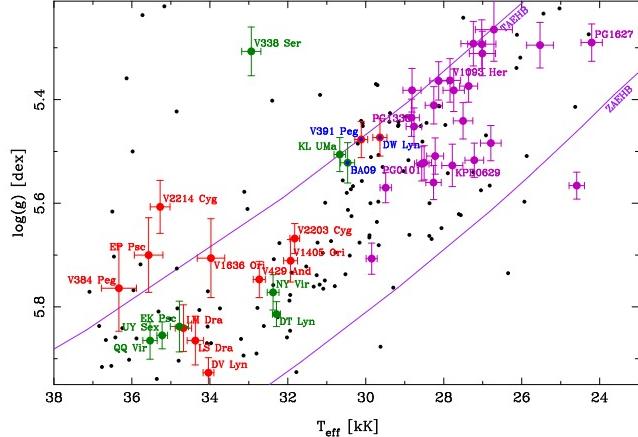


Fig. 2 Section of the T_{eff} – $\log g$ plane where the EHB stars are located. Pulsators with temperatures and gravities in the BG survey are marked with big symbols and error bars. Small symbols without error bars are stars not observed to pulsate. In the online version the colors indicate short period pulsators with (green) and without (red) published asteroseismic solution, long period pulsators (magenta) and hybrid pulsators (blue core).

Most recently, Green et al. (2008) presented a uniform high signal-to-noise low-resolution survey of a substantial sample including most known hot subdwarf stars brighter than $V = 14.2$, using the university of Arizona 2.3 m Bok telescope (hereafter referred to as the Bok-Green or BG survey). From this large sample the clearest picture of the EHB to date emerges (Fig. 1). Most stars in the diagram are clearly well bound by EHB models for a narrow mass distribution. Most of the remaining stars are consistent with post-EHB models, but could also fit core helium burning objects with higher than canonical masses. The most helium rich objects, however, appear to form their own sequence, which cannot be explained by canonical EHB models. Although the details of this survey are still under analysis, several new features have been noted. The sequence of He-rich objects around 40 kK is not compatible with current evolutionary scenarios, since post-EHB and post-RGB objects pass too rapidly through this region of the T_{eff} – $\log g$ plane to produce the observed clustering, but the *late hot flasher* scenario (Sweigart 1997) holds some promise.

The binary interaction scenarios that permit a star on the RGB to be stripped of its envelope to leave a helium burning core that will settle on the EHB are quite well understood (Han et al. 2002, 2003). Depending only on the mass ratio of the system, the orbit will either contract or expand. If the expanding mass donor is more massive than the accretor, the orbit will shrink catastrophically and the system enters a common envelope (CE) phase. As the orbit shrinks further due to friction, orbital energy is deposited in the envelope, spinning it up and eventually the envelope will be ejected. If the companion is more massive than the RGB donor, the orbit expands and no CE is formed. In this stable Roche lobe overflow (RLOF) scenario the orbital period can end up as

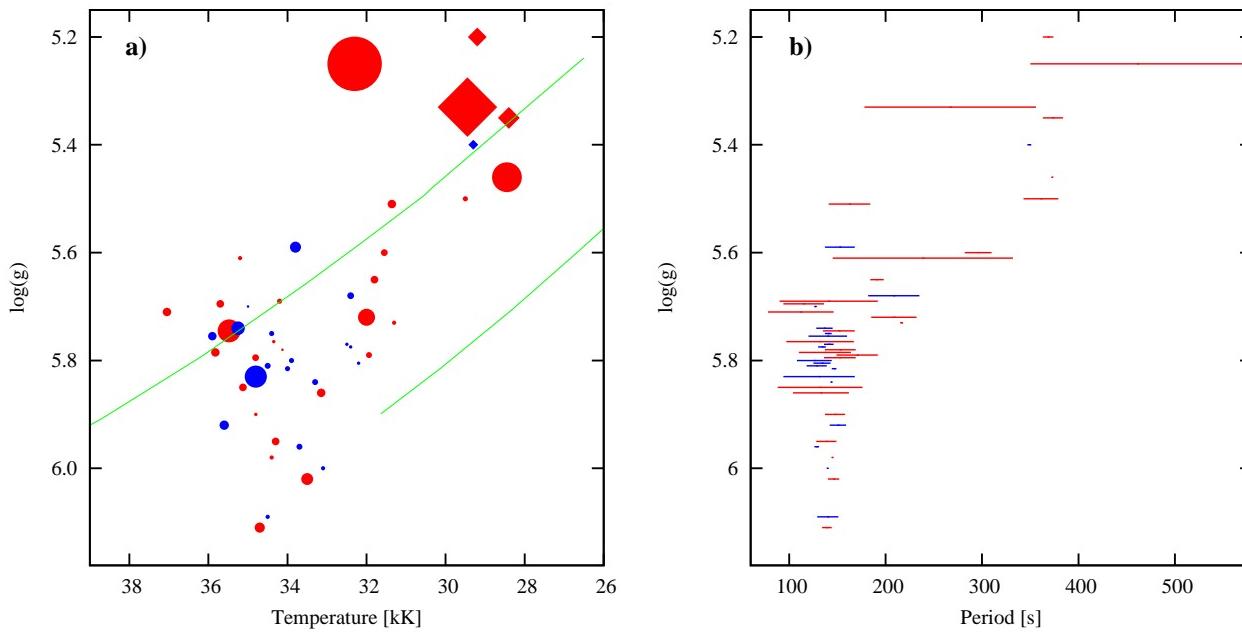


Fig. 3 The properties of the 49 known sdBV stars are summarised in Østensen et al. (2010a). These figures appear in that paper, and show: a) T_{eff} – $\log g$ diagram for the 49 sdBVs. Circles indicate V361 Hya type pulsators and diamonds indicate hybrid DW Lyn type pulsators, and the size of the symbols is relative to the pulsation amplitude. The 19 sdBVs from the NOT survey are shown in blue, and pulsators from other surveys in red. The green lines indicates the EHB, as in Fig. 1. b) P – $\log g$ diagram for the same pulsators. The bars indicate the range of detected pulsation periods in any particular star, excluding harmonics and g -modes.

long as 2000 days. The formation of single sdB stars is more problematic. A possible formation path is the merger between two helium white dwarfs first proposed by Webbink (1984). This can easily produce many of the He-rich subdwarfs, but it is hard to understand how sufficient hydrogen can survive for them to end up with significant envelopes, as most EHB stars have. The enhanced stellar wind models proposed by D'Cruz et al. (1996) are a possibility, but it is hard to explain why RGB stars should display such a large variability in wind mass loss rates that is required to explain the observed distributions. For a discussion of the more speculative scenarios, see Østensen (2009).

2 Asteroseismology

Rapid pulsations in sdBs were first reported by Kilkenny et al. (1997), after their discovery of the prototype, V361 Hya (EC 14026-2647), and several similar objects. These pulsators span the hot end of the EHB strip and pulsate in p -modes of low ℓ orders with photometric amplitudes up to 6%. The pulsation periods range between 100 and 400 s, and 49 such stars are known in the literature to date (Østensen et al. 2010a). One of these, V338 Ser (PG 1605+072), has periods reaching almost 10 minutes, but stands out as it sits well above the EHB (Fig. 3 and 2), possibly because it is in a post-EHB stage of evolution.

Long period pulsations became known when Green et al. (2003) reported pulsations in V1093 Her (PG 1716+426),

with periods between one half and two hours. They also found that as many as 75% of sdB stars cooler than ~ 30 kK display some level of pulsations at these periods, but due to atmospheric effects at similar time-scales and strong multi-periodicities, they are hard to reliably characterise. These stars span the EHB from the coolest sdBs up to the domain of the V361 Hya stars (Fig. 2). The pulsations were identified with high radial order g -modes by Green et al. (2003), and their amplitudes are very low, typically 0.2 %.

When Schuh et al. (2006) found that a known V361 Hya star, DW Lyn (HS 0702+6043), was displaying the g -modes of a V1093 Her star simultaneously with short period p -modes, the existence of hybrid pulsations was established. Such stars are now often referred to as DW Lyn stars. A final class of pulsations in hot subdwarf stars was discovered by Woudt et al. (2006) in the hot sdO/F-star binary J17006+0748. This object is very faint at $g = 17.4$, and no other pulsating sdO star has yet been reported.

For a discussion on the driving mechanism and interior structures of hot subdwarf pulsators, we refer the reader to the article by Kawaler (this issue). In this review we will focus on the methods that have been used to identify pulsation modes in the sdBVs, which will be described in the following sections.

2.1 Period matching

The exceptional amplitude of the dominant period in Balloon 090100001 has hinted towards a radial nature, and sev-

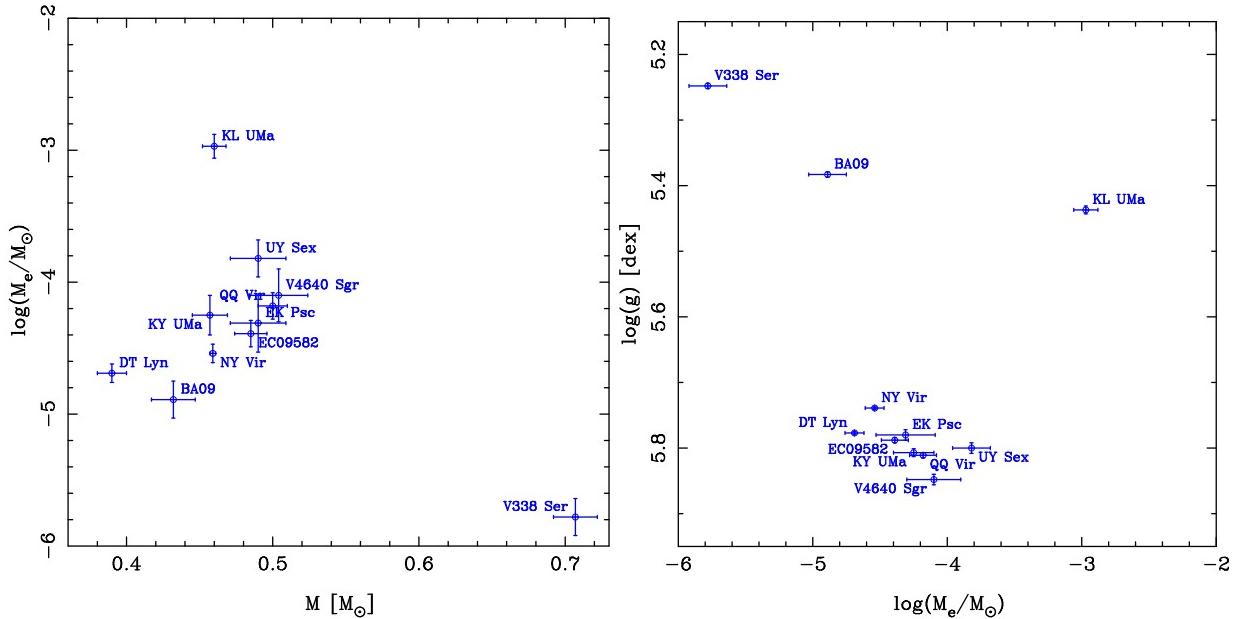


Fig. 4 Published asteroseismic solutions for ten V361 Hya stars. The left hand panel shows total mass plotted versus envelope mass, and the right hand panel shows envelope mass versus surface gravity. Note that only the optimal solution is shown even if the papers discuss several possible ones.

eral mode identification methods have now confirmed that suspicion. van Grootel et al. (2008) have successfully applied the forward method to Balloon 090100001, demonstrating some peculiarities in the model predictions. Their optimal solution for the main mode, when using no constraints, is $\ell=2$, which is not reconcilable with the spectroscopic data. However, by imposing mode constraints from multicolor photometry they do find asteroseismic solutions that agree with all observational data. Curiously, the physical parameters for the constrained and unconstrained fits are almost identical, even if the mode identification changes for half the modes considered. This peculiarity arises from the high mode density and the way the modes are distributed in period space.

With a recent update of the forward modelling code, Charpinet et al. (2008) have produced a very convincing model for the eclipsing binary system NY Vir (PG 1336-018). This star has been particularly challenging since it is rapidly rotating, due to being in a tidally locked orbit with the close M-dwarf companion. The rotational splitting of modes with different m produces a particularly rich pulsation spectrum. Charpinet et al. (2008) use asteroseismology to discriminate between three solutions from the binary orbit published by Vučković et al. (2007), and finds that the intermediate model with a mass of $0.47 M_{\odot}$ is clearly favored. This solution is also the only one consistent with the $\log g$ from the BG survey (Fig. 2).

To date, eleven asteroseismic solutions computed with the forward method have been published. They were summarised in Randall et al. (2007) for the first seven, and in Fig. 4 the new solutions by van Grootel et al. (2008), van Spaen (2008), Charpinet et al. (2008) and Randall et al. (2009) have

been included. A feature of the asteroseismic modelling is that T_{eff} is rather poorly constrained, and a better value can usually be provided from spectroscopy. The surface gravity, total mass, and envelope mass fraction all have very small associated errors in the asteroseismic solutions, so we plot only these in Fig. 4. The distribution of masses is not as concentrated around $0.47 M_{\odot}$ as most canonical evolutionary models have presumed, but all points are well within the permitted ranges for synthetic populations considered by Han et al. (2002, 2003). Except for two outliers, all the stars appear to form a trend with envelope mass, M_e , increasing with total mass, M . Although this feature has not been accounted for by evolutionary calculations, it could occur as a natural consequence of a higher core mass requiring more energy to remove the envelope. More disturbing is the lack of any clear trend in envelope mass versus surface gravity, as is clearly demanded for canonical EHB models. The scatter in the high gravity objects is easily explained by their spread in mass, and KL UMa fits well with the expected $M_e/\log g$ trend. But the unusually low envelope masses for BA09 and V338 Ser are hard to explain, and may indicate that the adopted models are too simplified to represent the seismic properties for these cases.

There are a few concerns with the forward matching method as used on the V361 Hya stars up to now. First of all, the models only match the observed frequencies to a precision of a few percent. The frequencies can be determined to within a μHz in a few weeks of observations (which is one fiftieth of a percent for typical short-period sdB pulsations), and a precision of $0.02 \mu\text{Hz}$ was reported for V391 Peg by Söderblom et al. (2002). Much more work on theoretical models are required to bring them closer to this precision level.

This requires non-adiabatic pulsation models to be connected to fully evolutionary models for sdB stars. Such evolutionary models must include gravitational settling and radiative levitation. Progress on the first point was reported recently by Hu et al. (2009), but the second point still remains to be solved. Another issue with the current model calculations is that they do not address the pulsation amplitudes of the modes.

Using photometric mode-ID has a distinct advantage on faint stars, but requires a rich pulsation spectrum. Multi-site campaigns can provide high frequency resolution and detect low amplitude modes. However, often, no unique solution for a particular mode is found, because modes with different ℓ 's can be found within the precision of the model fit.

V1093 Her stars are much harder to do with this method, since the longer periods require correspondingly long time-bases in order to resolve the pulsation spectra. Only one long baseline study has been attempted; PG1627+017 (Randall 2006). From 300 h of photometry they found 23 periods with amplitudes between 0.4 and 5 mma. However, as gravity modes probe the interior of these stars, reliable mode identification from period matching can only come from models that include detailed interior structure.

2.2 Spectroscopic mode ID

Telting et al. (2008) presented the first study of line-profile variations in these stars based on high-resolution spectroscopy, again using Balloon 090100001 as the preferred target due to its strong dominant mode. While the line-profile method is well established for various main sequence pulsators, its application to the faint sdB stars requires substantial investments in terms of telescope time, which has hampered its use. With the preliminary results on Balloon 090100001, Telting et al. (2008) demonstrated that the ℓ of the main mode must be either zero or one.

It is possible to make a direct mode-ID of a single pulsation period from phase diagrams of sharp spectral lines, but that method requires both high S/N and that the star has a significant rotation. Except for a few sdB stars that are in short period binaries and therefore have tidally locked rotation, all sdB stars studied so far show extremely low rotation velocities ($v \sin(i) \leq 5$ km/s), which explains why this method have not been successful yet on these pulsators.

The main problem with using spectroscopic mode identification techniques on the hot subdwarf pulsators is the extraordinary effort in terms of telescope size and time required in order to get the required S/N. So far it has only been feasible on a few pulsators with a high amplitude main mode, and even then phase folding of extensive time series has been required. In multi-mode pulsators with many peaks of comparable amplitude, interference between the modes produce broadening in the phase folded line profiles which further hamper their interpretation. But progress is still being made both in the observational methods and in the methods used to interpret the observations.

2.3 Amplitude ratios from multi-color photometry

The amplitude ratio method allows unique identification of ℓ for all modes in a pulsation spectrum. This is done by comparing the ratio of pulsation amplitudes as observed in different photometric bands, with amplitudes computed from models that include limb darkening effects. The method requires very high accuracy on the amplitudes in order to distinguish between $\ell = 0, 1, 2$ modes (Ramachandran et al. 2004), but can easily distinguish between the low ℓ modes and $\ell = 3, 4, 5$. To achieve the required precision, simultaneous observations in several bands are required. The clever design of ULTRACAM (Dhillon & Marsh 2001), in which dichroics are used to split the light into three beams that permits truly simultaneous observations in three passbands, has made such observations possible. ULTRACAM observations on V361 Hya stars were first obtained by Jeffery et al. (2004), where they demonstrated that modes of $\ell = 3$ and 4 must both be present in their stars in addition to $\ell \leq 2$ modes, but they did not have sufficient data to distinguish between the low ℓ modes. More recently Vučković et al. (2010) presented six nights of ULTRACAM photometry of EO Ceti (PB 8783) which does have the required accuracy for mode-ID. However, in this case the result is hampered by the fact that EO Ceti has a strong F-star companion, which gives a light-contribution that is more severe in the red part of the spectrum, and therefore skews the amplitude ratios. But they did manage to prove that the photometric amplitude ratios remain constant even when the amplitudes themselves appear to vary in time, which is encouraging as such amplitude variability have been observed in just about all V361 Hya stars (Kilkenny 2010).

2.4 Combination method: multi-color + RV

Amplitudes from multi-color photometry can be used in combination with radial velocity amplitudes from spectroscopy in order to obtain more reliable discrimination between low ℓ order modes. The method was first introduced by Daszyńska-Daszkiewicz et al. (2003), and applied to Balloon 090100001 by Baran et al. (2008), where they obtained a clear preference for $\ell = 0$. More recently, Baran et al. (2010) applied the method to QQ Vir, and again found a preference for $\ell = 0$ for the dominant main mode, but in this case the discrimination is not clear enough to exclude $\ell = 1$. This method has a clear advantage in that it does not require such an extreme S/N level as the multi-color method alone. The catch is that the spectroscopy must be obtained close to the same time as the photometry in order to ensure that the pulsation amplitude has not changed between the times of the photometric and spectroscopic observations.

3 Progress in observations

Multi-site campaigns have been organised to observe sdB pulsators since the time of the first discoveries (Kilkenny et al.

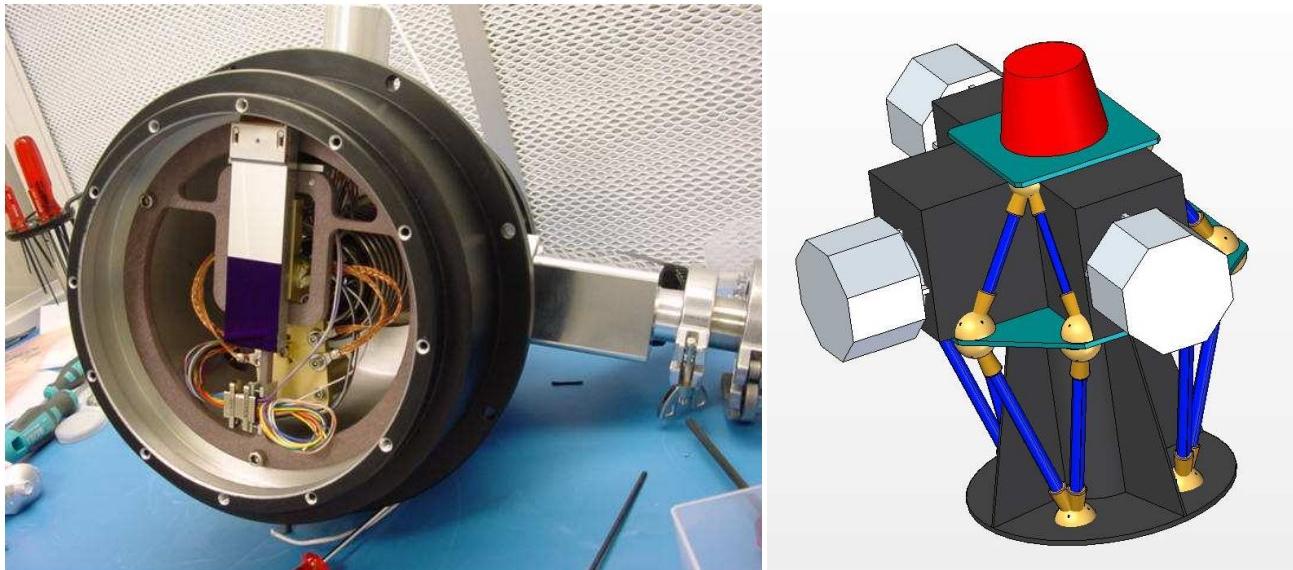


Fig. 5 LEFT: The upgraded MEROPE II camera during the mounting of the large format frame-transfer CCD at the *Mercator Telescope*. The 13 cm long CCD package requires a specially designed asymmetric cryostat design due to the extensive image storage area (silver coated), clearly visible above the anti-reflection coated imaging area. RIGHT: The design for the three-channel MAIA camera will apply three such CCDs in separate cameras kinematically mounted in the Nasmyth focus of *Mercator*.

1999), in order to reduce one-day aliases in the Fourier spectrum. But combining data from different observatories using different filters is a method that is riddled with problems, when high precision is required not just on the frequencies but also on the amplitudes. Since the amplitudes of the pulsations are stronger in the blue, individual modes may appear to have different amplitudes for observers with different passbands. This is not trivial to correct for since the color dependence of the pulsation amplitudes also depends on the order, ℓ . The only way to obtain continuous time series photometry unaffected by the diurnal cycle and atmospheric extinction effects is to observe from space.

3.1 The future is in space

Data from the *Kepler Mission* are already revolutionising the prospects of white light asteroseismology on the hot subdwarfs. The unprecedented precision and exceptionally high frequency resolution obtainable by space based photometry will certainly have a major impact on our understanding of the hot subdwarfs. While asteroseismology of the V361 Hya stars have proven successful in many cases, only with the new range of precision and resolution obtainable from space can we expect to achieve successful asteroseismology of the V1093 Her pulsators for the first time.

The only problem with *Kepler* is its limited field of view, which will provide a restricted number of targets to work with. The field is expected to contain about four V361 Hya stars and perhaps eight V1093 Her stars (Silvotti 2004). A spectroscopic survey of the candidate subdwarf pulsators have already been completed, and will be presented together with the first *Kepler* results in Østensen et al. (2010b). While

the number of pulsators expected is quite small, at least for the V1093 Her stars the sample should be sufficiently large that we are certain to enter a new era of asteroseismology that will fundamentally change our understanding of the subdwarf B stars. But for all the known V361 Hya stars in the literature, our observation tools are rooted in ground-based facilities for a long time yet.

3.2 Better multi-color photometry

ULTRACAM combines two key design features that makes it uniquely suited for mode identification of the rapidly pulsating hot subdwarf stars. The first, as mentioned earlier, is the splitting of the incoming light beam into separate channels, which allows truly simultaneous multi-band photometry. The second is the use of frame-transfer CCDs, which eliminates the dead time associated with the readout period, which is typically between 20 and 80 seconds for reading out the full frame on a regular CCD chip, comparable to the pulsation period of the V361 Hya stars. The frame-transfer concept divides a CCD chip into an integrating half and an image storage area, so that one frame can integrate while the previous frame is being read out. ULTRACAM is the only instrument that combines both these features. The only catch with frame-transfer CCDs, and the reason why they are avoided by most new CCD cameras is that they are only commercially available in relatively small format. The three ULTRACAM CCD chips have only 1024×1024 pixels, while the standard for astronomical CCDs have for a long time been at least 2048×2048 pixels. This means that ULTRACAM has a smaller field of view than ideal (assuming a typical pixel size of 0.2–0.3 arcsec/pixel), and this can im-

pact seriously on the precision of photometric amplitudes. For instance, Vučković et al. (2007) reported that they were unable to locate a reference star with a significant brightness in the *u*-band in the vicinity of NY Vir when observing with ULTRACAM on the VLT, and were therefore unable to calibrate the time-series properly. While the light-curve could be recovered by using a scaled version of the *g*-band light-curve for the differential photometry, this method may adversely impact the precision required for the amplitude ratio method, as the *u*-band is the one that provides the largest discrimination between modes. Another problem with ULTRACAM is that the camera is only available for a very limited number of nights each year, as it is a traveling visitor instrument.

Motivated by the success of the ULTRACAM design the instrumentation group in Leuven have made an improved design for a three-channel camera, to be permanently mounted on the *Mercator Telescope* at Observatorio del Roque de los Muchachos on La Palma. This telescope is owned and operated by K.U. Leuven, and through our ongoing instrumentation program we have in 2009 commissioned a high-resolution multi-fibre spectrograph, HERMES.

The development of new cameras ideally suited for high-speed CCD photometry was made possible by the unfortunate termination of the ESA/EDDINGTON asteroseismology space mission. At the time the decision to cancel the mission was made, E2V had already designed and developed new frame-transfer CCDs for EDDINGTON. After an application to ESA, we obtained four of the prototype CCDs on a permanent loan. These CCDs are large format frame-transfer devices with an image format of 2048×3074 pixels, permitting a six times larger effective area than currently available frame-transfer devices. The first of these devices was installed in a regular single-channel CCD camera replacing the aging MEROPE camera in the Cassegrain focus of *Mercator* (Fig. 5). The remaining three will be installed in the *Mercator Advanced Imager for Asteroseismology* MAIA, a three channel CCD camera of comparable design to ULTRACAM, which is currently being built in Leuven, and scheduled for commissioning at *Mercator* next year (Vandersteen et al. 2010).

4 Conclusions

Astrophysics of EHB stars is a rapidly advancing field with exceptional challenges, due to their complex formation paths. Progress is still being made on evolutionary models, but much remains to be done, particularly with respect to the formation of single sdBs. Asteroseismology is in an ideal position to test the different formation scenarios, but the models of the interior must be made precise enough so that they can reliably identify features of the stellar interiors that remain distinct tracers of their evolutionary history, even when their surface atmospheric parameters remain indistinguishable (Hu et al. 2008, 2009).

But important questions about the interiors of the EHB stars still remain. The current models predict that all EHB stars should pulsate as soon as radiative levitation and gravitational settling have accumulated sufficient iron group elements in the driving region. But only 10% of stars in the V361 Hya instability region are found to pulsate. While Jeffery & Saio (2007) have speculated that this accumulation can be disrupted by the vertical motion of strong *p*-mode pulsations, it is hard to understand how this mechanism can be reconciled with the time scales of the amplitude variations that have been observed in these stars (Kilkenny 2010). Another possibility was recently put forward by Théado et al. (2009), who explore how iron-group enhanced layers lying on top light elements can lead to convection through “iron fingers” (similar to the so-called “salt fingers” that are responsible for thermohaline convection in the oceans). Such convection can occur on timescales of a few thousand years, much shorter than classical diffusion. Asteroseismological models may have to include these types of diffusion in order to adequately represent the excited modes and amplitude variation observed in EHB stars.

For V361 Hya pulsators mode identifications have been made on a number of stars with several different techniques that complement each other, but not always producing identical answers. The high observed mode density is a problem for frequency matching techniques, especially when the predictive precision of the models are only on the order of a few percent. Mode identification from spectroscopy and multi-channel photometry has the advantage that they can identify the ℓ order of modes without any assumptions on the internal structure of the star. When combined with radial velocity measurements this technique is particularly powerful. More instruments that can support such observations will be required in order to facilitate more extended application of these techniques. Three channel cameras can go a long way towards direct mode identification on their own, but simultaneous radial velocity measurements would be ideal. In principle, a low-resolution spectrograph can do this, but current instruments are not well suited for photometric precision. A minimum requirement is simultaneous observation of a reference star in order to properly calibrate the photometry. This requires a rotator in combination with an atmospheric dispersion corrector in the light beam in order to avoid chromatic airmass effects. Such instruments are currently not available for the sparsely populated fields where we find the hot subdwarfs.

The low amplitudes and long periods make it very difficult to establish detailed pulsation spectra for V1093 Her stars, and even when it can be done the high mode density makes it difficult to assign modes to the observed frequencies. But *g*-modes are particularly interesting because they probe deep into the stellar interior. This is a significant challenge for the future due to the long time-base required to reliably determine the longer pulsation periods in these stars. The recently launched *Kepler mission* (Christensen-Dalsgaard et al.

2007; Borucki et al. 2010) provides an excellent opportunity for asteroseismology of compact pulsators.

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